High-Range Laser Light Bandwidth Measurement and Tuning

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ABSTRACT

High performance lithography is increasingly demanding light sources to deliver laser light over a much larger range of stabilized bandwidths. The applications range from improved optical proximity correction (OPC) to the high-speed printing of vias and contact holes, through a process called focus drilling. Several advances in light source technology must integrate to provide the improved bandwidth performance required by the industry.

This paper will outline three of the core technologies developed by Cymer and integrated into its most advanced XLA™ and XLR™ series light sources to meet this need. Novel improvements in line narrowing offer the actuation necessary to tune the bandwidth over the large range. Advanced bandwidth metrology yields accurate measurements of the bandwidth over the wide range. And new controls and feedback algorithms provide the integration to stabilize the bandwidth to the desired target. The result provides laser light bandwidths that can be tuned to and accurately stabilized at any spectral E95 target from 0.3 pm to 1.6 pm, while maintaining all other laser performance parameters. The feature is called focus drilling. Focus drilling extends the utility of Cymer XLA and XLR lasers by adding more flexibility to the light source, allowing the end-user chipmaker to select the exact properties of the laser light necessary for a wider range of process steps.

The article will discuss the above technologies and emphasize their important aspects. It will also highlight some of the key performance aspects using data from Cymer's testing. Some of the design features and trade-offs will be provided, and a few of the relevant metrics will be presented and justified. Finally, potential future improvements to the technology will be presented.

Keywords: laser, bandwidth, focus drilling, laser metrology

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1. INTRODUCTION

Advanced lithography systems are offering rapidly increasing performance in response to market demands. Among these performance improvements are better reliability, increased availability, and higher throughput. Throughput is increased through many means, including via the laser light source. To help increase throughput, the laser can provide tighter stability of light properties, such as better dose stability; new features, such as bandwidth tunability; or a wider range of operational capability, such as higher power. Cymer has developed these and other important improvements throughout its history.

Cymer is continuing to improve its XLA and XLR series DUV light sources by developing the capability to operate over and tune to a much wider range of laser light bandwidths. Such capability can be applied to, for example, a focus drilling system, where very high bandwidths can reduce loss of focus latitude when printing features such as contact holes and vias (see Reference [1]), while maintaining process stability. While methods to significantly increase bandwidth range have been proposed in the past (see Reference [2]), the demonstrated maturity of the technology described in this paper allows a robust, stable, and seamless solution. This new technology is currently deployed at a high volume chipmaker.

The higher bandwidths are achieved mostly by a new line narrowing module (LNM) with an advanced bandwidth actuation mechanism. However, to properly stabilize and report the higher bandwidths, fundamentally new bandwidth metrology is required, and a new control scheme is needed to integrate these. These three key elements are described, with emphasis on capability and important technological aspects. Some Cymer test data is given showing examples of the new capability, and some trade-offs will be discussed. Finally, potential enhancements to the technology are offered.

2. LINE NARROWING IMPROVEMENTS

Cymer developed the new focus drilling LNM to provide the significantly wider laser light spectra and the ability to rapidly change it from narrow to broad. It is coupled with the existing Cymer Active Bandwidth Stabilization™ (ABS™) technology to provide a dual stage actuation of bandwidth (see Reference [3]). This allows existing ABS laser systems to perfectly retain their existing low bandwidth performance, while adding the high bandwidth capability as an upgrade. The new LNM fits within the existing LNM location in the laser, and requires only minimal additional hardware and connections to enable it. All of these features imply the high-range bandwidth system adds the new capability seamlessly, with minimal upgrade downtime, and without compromising existing performance.

The maximum bandwidth with the new LNM, as measured by spectral E95[2] (hereafter called simply E95), is increased to over 1.6 pm from a prior typical maximum of 0.5 pm. A recently introduced bandwidth metric, called Convolved Bandwidth (CBW)[3], can also be increased to over 1.5 pm. Figure 1 shows these metrics against the new actuation in the LNM. Note that the existing ABS bandwidth actuation range is maintained, able to achieve up to 0.5 pm. Importantly, with this actuation scheme, the spectrum is broadened with very little impact to other laser operational parameters such as wavelength stability and energy stability.

The speed of the new actuation is also an important performance metric, as it defines the stabilization and switching capability of the final closed loop system. The actuation responds as a first order asymptotic, with a time constant of 650 milliseconds, delay of less than 50 ms, and highly symmetric response with no hysteresis[4]. Figure 2 shows some step responses.

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[2] Spectral E95 is the standard bandwidth metric among immersion systems.
[3] CBW is basically a measure of the laser spectrum's "appearance" to the optical system of the scanner. It will be discussed in more detail in Section 3.
[4] The CBW response may appear to have longer delay and be slower in the negative direction; this is due to the CBW's insensitivity to actuation at low values, and not actuation speed. A compensation method is described subsequently.

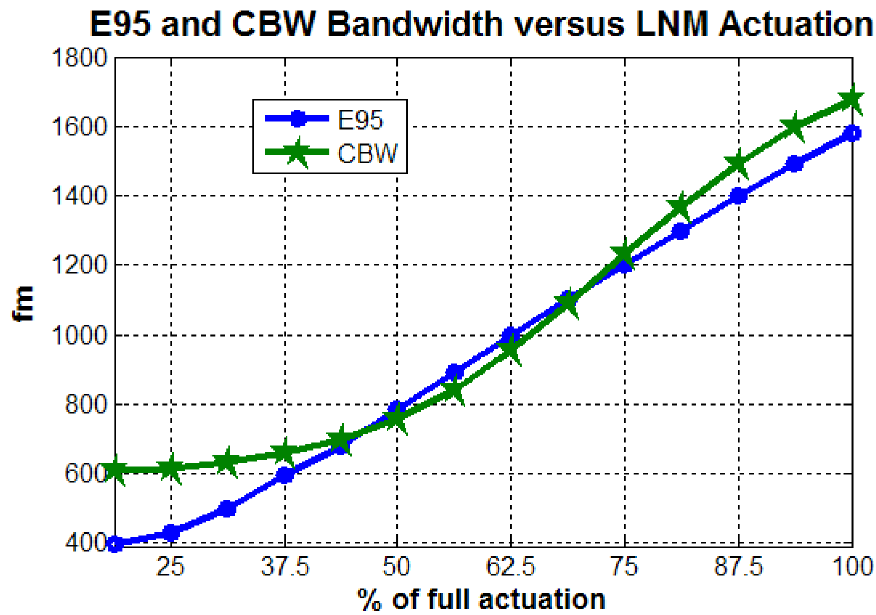

Figure 1. Bandwidth versus actuation, showing large nonlinearity of CBW

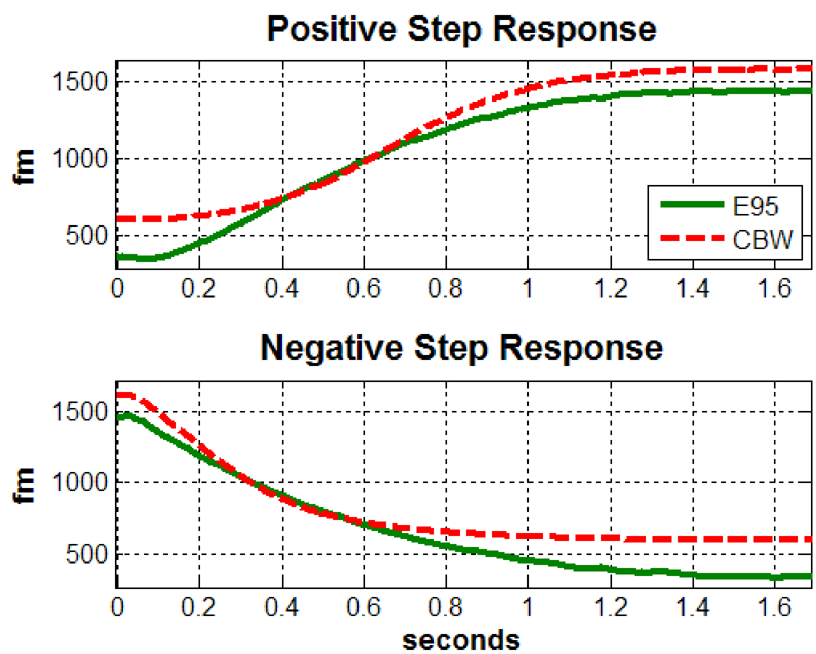

Figure 2. Bandwidth actuation speed of response

3. ADVANCED BANDWIDTH METROLOGY

A bandwidth metrology that accurately measures the laser's spectrum over the very wide range provided by the new actuation mechanism discussed in section 2 was required. It must be capable of measuring not only the standard metrics of E95 and Full Width at Half Maximum (FWHM), but also the spectral shape, with the introduction of the new CBW metric. Moreover, it needs to perform these tasks at a high rate sufficient to report on a burst-by-burst basis.

Figure 3 shows the bandwidth metrology process steps. The etalon fringe data is first pre-processed by an algorithm that continually estimates and compensates for the image sensor reference changes and error sources to minimize effects from limited mechanical tolerances and thermal drift. The new bandwidth metrology then recovers an estimate of the spectrum that is optimal in the least-squares sense, by using advanced proprietary signal processing on the pre-processed and prepared sensor data and calibration factors. The post-processor filters in both the sample and spectral domains to minimize de-convolution process noise (e.g. Gibbs oscillations) and speckle effects. All these processes are combined and tuned in unison to yield the optimal spectrum estimate, which is the most accurate given the system characteristics. Figure 3 shows the process steps graphically.

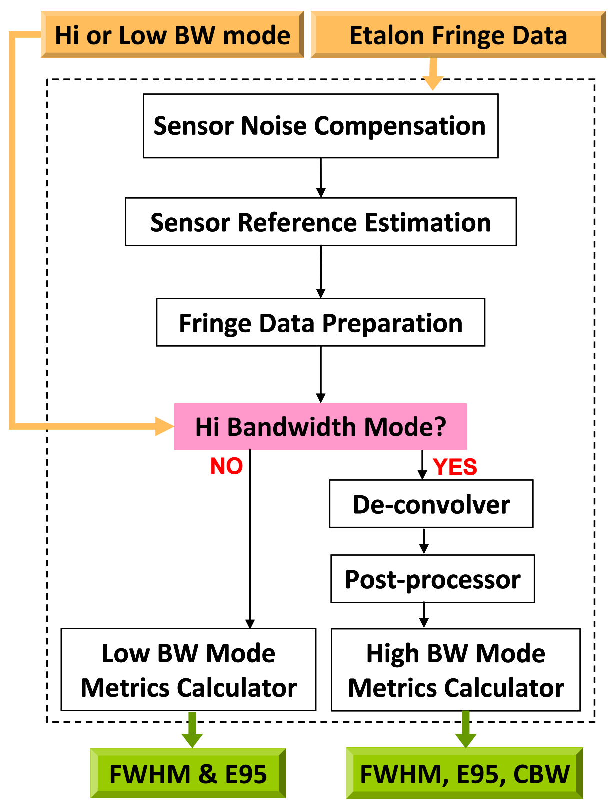

Figure 3. Bandwidth metrology process

There are some trade-offs. Filtering can reduce, but not eliminate, noise and speckle effects. Longer sensor exposures, which tend to average noise and speckle, often yield a more accurate measurement. Longer exposures, however, come at the cost of reduced reporting frequency. This trade-off effectively places a bound of spectrum measurement accuracy for a given reporting rate. The new metrology can be adjusted to operate anywhere within this trade space: from longer-exposures and better accuracy, to shorter exposures with less accuracy. The parameters are tuned to yield performance very near the accuracy bound for the chosen regime. For a reporting rate of once per burst, the accuracy is shown in Figure 4.

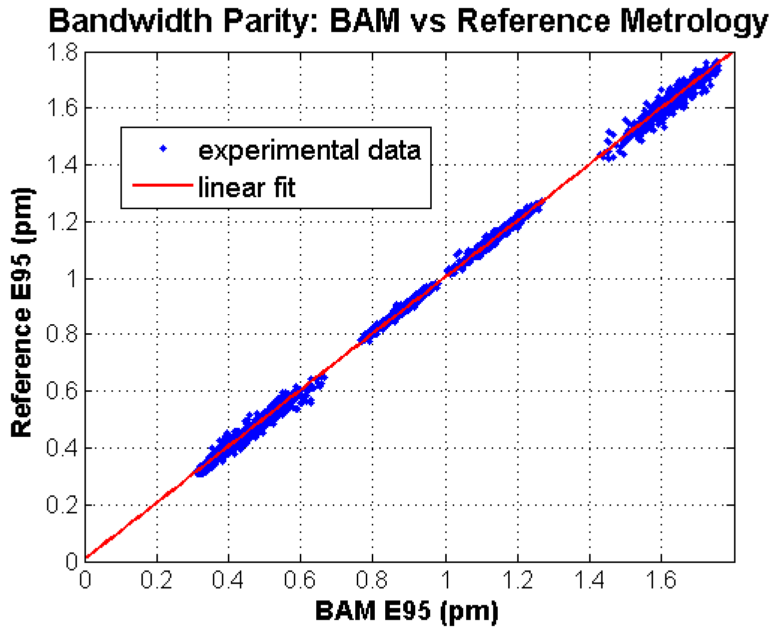

Figure 4. Parity of new metrology versus reference metrology

As with the new LNM, the new bandwidth metrology module (BAM) also operates identically under the normal low bandwidth modes as existing metrology modules, as shown in Figure 3 (see also Reference [4]). This allows the system in low bandwidth mode to perform the same after the upgrade as before, minimizing disruptions and process variations. The metrology switches between the low and high bandwidth modes smoothly and quickly when the system requires it. The system is calibrated to provide maximum accuracy in both modes.

The new CBW metric is computed in the new metrology. It is the FWHM value of a convolved spectrum obtained by convolving the laser spectrum with an "image function", representing the spectral response of some part of the system receiving the light. Note that such a convolved spectrum is the actual effect of the laser spectrum on this part of the system. Figure 5 shows the process graphically.

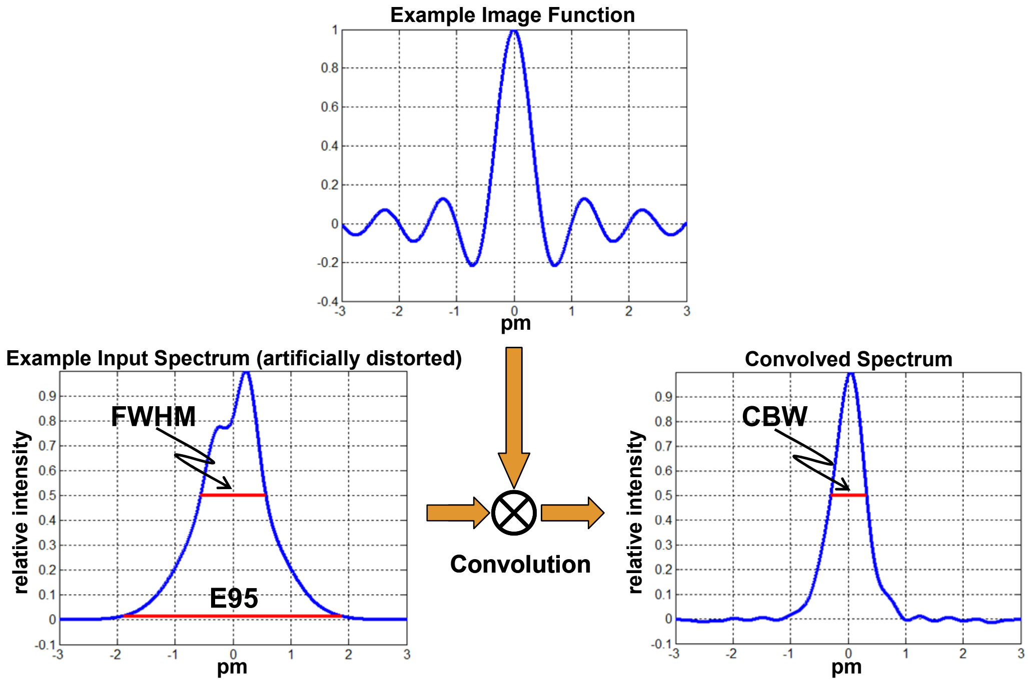

Figure 5. Computation of convolved spectrum and CBW

4. NEW CONTROLS AND INTEGRATION

The new hardware technologies discussed in the previous sections require integration and control to achieve and maintain specified bandwidth performance. Two key performance metrics are bandwidth stability (or disturbance rejection) and time to switch between low and high bandwidth operation. Each of these is enabled through several new controls technologies, some acting together and others acting independently. The system may operate in two modes to coincide with the metrology's modes: low bandwidth and high bandwidth. Within these modes, the target bandwidth can be selected to any value within the system's operating range.

When the system is operating in low bandwidth mode, stability as achieved exactly as existing technologies (see Reference [3]), which eliminates performance variations and disruptions when upgrading to this new technology. When the system is operating in high bandwidth mode, bandwidth stability is achieved through both closed and open loop control. The closed loop uses the new bandwidth metrology as the feedback sensor, the new line narrowing as the actuation, and advanced high-performance feedback and feed-forward algorithms to control and integrate these. Figure 6 shows the control system architecture. The system is capable of controlling E95 or CBW based on user commands. The feedback algorithm uses integral feedback with compensation for resulting phase lag and intergrator wind-up. The feed-forward algorithm works by estimating the bandwidth-versus-actuation gain and inverting it. The estimation is based on both the current actuation command and knowledge of Figure 1. Therefore, depending on whether E95 or CBW is being controlled, the feed-forward algorithm selects the appropriate gain. This reduces design and implementation complexity by allowing the feedback algorithm to remain unchanged between E95 and CBW control, since the loop will always be tuned as system whose bandwidth-versus-actuation gain is near unity. Performance of this closed loop, compared to open loop, is shown in Figure 7, demonstrating the rapid convergence to large artificially induced step disturbances and large attenuation of a large artificially induced sinusoid disturbance.

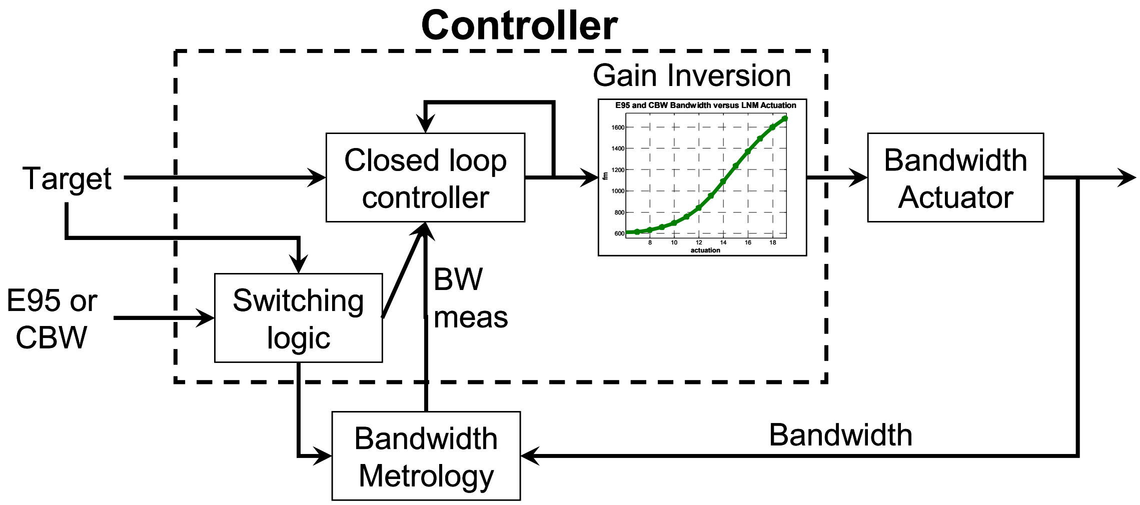

Figure 6. Bandwidth controller architecture

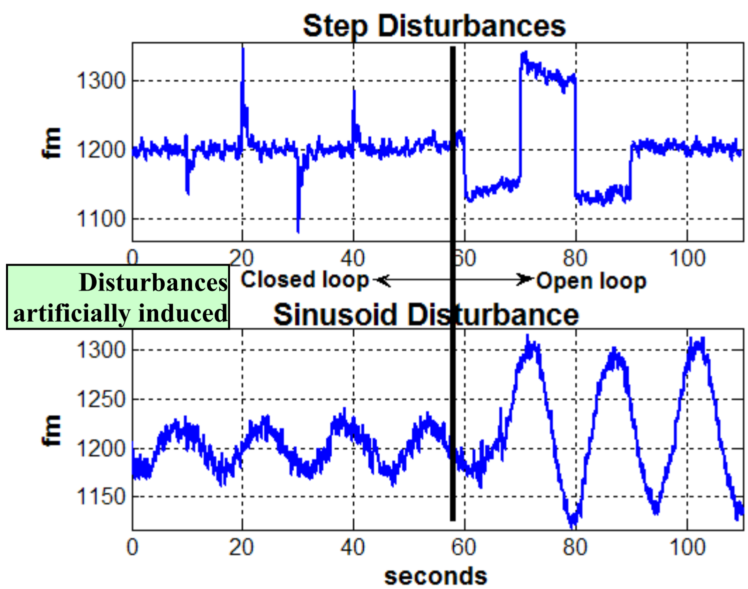

Figure 7. Closed loop performance under various disturbances (artificially induced); compare to open loop.

As mentioned, the target bandwidth can be changed at any time to any operational value. To maximize the speed when switching between different bandwidth targets, the controller uses a pre-drive mechanism and knowledge of Figure 1 to effectively select the LNM actuation needed for any new target. The closed loop removes any residual error. The performance of this switching scheme is shown in Figure 8. Comparing this to the step responses in Figure 2 shows the closed loop switching achieves nearly maximum possible performance. Additionally, if the system operates for an extended period (several days or weeks) in high bandwidth mode before returning to low bandwidth mode, measurable drift in performance can occur in the low bandwidth mode. To counteract this effect, a secondary closed loop, using the original ABS actuation and sensing, is used to assure that the bandwidth in low bandwidth mode is restored to the desired target.

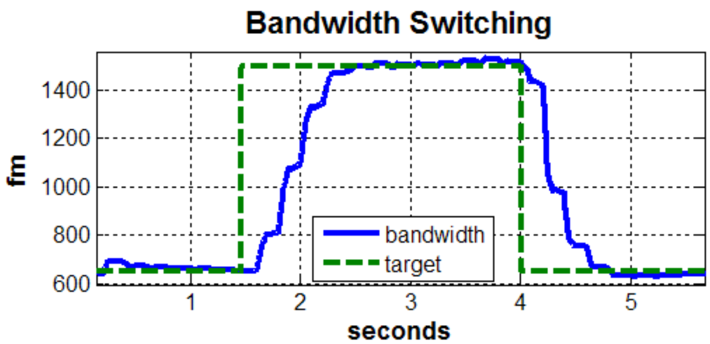

Figure 8. Bandwidth switching performance.

Large changes in bandwidth have the potential to disturb the laser's efficiency. Because well regulated efficiency is so important to the lithography scanners, the control system also includes several components to assure efficiency changes are managed and controlled. The system will observe any changes in efficiency, adapt to them quickly, and restore normal operation all within the time required to change the bandwidth to a new target.

Finally, the new controller manages the new metrology module by commanding it to switch to the desired mode (low or high bandwidth) at the appropriate times, and by maximizing use of the available data. For example, the low bandwidth mode metrology provides a fully updated bandwidth reading more frequently than the high bandwidth mode. The controller can then be made faster in this mode.

5. BANDWIDTH CONTROL POTENTIAL ENHANCEMENTS

As the lithography industry continues to evolve and progress, it is expected that tighter bandwidth stability, and more rapid bandwidth tuning will be required to maintain and increase throughput. The technology described in this paper can be enhanced in a relatively straightforward fashion to yield all of these improvements. Faster tuning can be accomplished through larger actuation hardware, or slight modifications of the hardware design. Tighter bandwidth stability is a matter of more advanced control algorithms that can observe and manage, in real-time, some of the nonlinear or transient effects of the bandwidth. Better stability can also be achieved through more fundamental means of control, such as laser alignments and tuning or by adding finer and faster actuation mechanisms.

6. CONCLUSIONS

Higher range laser light bandwidth can provide a significant jump in lithographic process capability and performance, improving focus latitude without loss of throughput, used when printing some specific features such as contact holes and vias. Cymer has introduced a new technology to provide a robust, switchable, and tunable high range bandwidth solution on its XLA and XLR series advanced laser light sources. New actuation mechanisms, advanced metrology, and tightly integrating controllers combine to yield the desired performance, which has been demonstrated in this paper, and at a large high volume chipmaker.

The technology is also robust, easy to upgrade, and does not disrupt or change any existing performance characteristics, even across the upgrade, ensuring continuous and seamless lithography cell operation. As the demands on bandwidth tuning continue to increase, this technology can be scaled well to meet these demands. It represents an added flexibility of Cymer light sources to the lithography manufacturer.

7. REFERENCES

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